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A CALORIMETRIC THERMAL NEUTRON DOSEMETER

Karsten Haack

Abstract. In order to attain a prescribed silicon resistance by neutron doping, an accurate, continuous measuring dosemeter is needed. The thermal flux density pattern in the irradiation facilities of a research reactor is subject to slow as well as fast changes during an irradiation cycle, thus impeding reliable prediction of the thermal neutron dose.

In the 5 silicon irradiation rigs in the DR 3 reactor thermal neutron dosemeters applying the calorimetric principle are used. The absorbed energy from (n, α)-reactions in a boral sample is lead through a stainless steel rod to the surroundings. The temperature drop between the rods ends is measured by a set of thermocouples. The delta temperature is proportional to the heat absorption in the boral sample and so proportional to the neutron flux density. The thermocouple signal is integrated in the instrumentation thus supplying a measure of the thermal neutron dose.

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October 1980
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The calorimetric dosemeter is cheap and robust. In a thermal neutron flux density of $4x10^{12}$ $ncm^{-2}s^{-1}$ the calorimeter response will decrease about 0.7% per year owing to burn-up of boron The outside dimensions of the instrument is 26 mm$^{\varnothing}$ x 30 mm.

The report gives design basis, construction details and some measurement data of the calorimetric dosemeter.

INIS descriptors: CALORIMETRIC DOSEMETERS, CRYSTAL DOPING, FLUX DENSITY, IN CORE INSTRUMENTS, IRRADIATION CAPSULES, NEUTRON DOSIMETRY, NEUTRON FLUX, SILICON, THERMAL NEUTRONS.

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LIST OF CONTENTS PAGE

1. INTRODUCTION

Doping silicon crystals with phosphorus by means of thermal neutron irradiation require a sensible and reliable dosemeter in order to obtain prescribed resistivity characteristics of the silicon material. The most convenient arrangement seen from a practical point of view is a continuous measuring dosemeter permanently installed in the irradiation device. However, an online dosemeter must possess properties as good reproducibility, fairly constant sensitivity and a long life, porperties which are not obtained by ordinary instruments when exposed to the radiation fields in a nuclear reactor.

Therefore the choice have fallen on a rod type calorimeter designed for high sensitivity to thermal neutron flux density and a reasonable long life.

2. MEASUREMENT CONDITIONS

The silicon irradiations are performed in the 4-VGR holes, e.g. vertical 10 cm$^{\varnothing}$ experiment holes in the graphite reflector, which is placed outside the D_2O-reflector of the DR 3 reactor at Risø.

The thermal flux densities in these experiment holes are in the range 3-5 x 10^{12} n $cm^{-2}s^{-1}$.

The fast flux density is 2-5 x 10^9 n $cm^{-2}s^{-1}$.

The γ-heating is ab. 20 Gy s^{-1} (20 mW g^{-1}).

The temperatures in the rigs are 120 - 250 ^{o}C at equilibrium at rated reactor power, 10 MW, depending of the silicon crystal loading.

The experiment holes are filled with air at atmospheric pressure.

The thermal flux density increases about 10% in average during the 23.5 days reactor cycle, mostly at the top of the experiment holes, while the thermal flux at the bottom of the holes remains fairly constant.

3. CONSTRUCTION OF THE DOSEMETER

The neutron calorimeter consists of a boral sample mounted on the free end of a stainless steel rod. See figure 1.

The other end of the rod is in good thermal contact with the surroundings through the thick calorimeter bottom and the supporting structure. The temperature drop along the rod is measured by two thermocouples. The assembly is enclosed in a sheath to keep steady heat transfer conditions through the air gap around the sample. The outer dimensions of the sheath are 26 mm diameter and 30 mm length.

The boral sample is disc-shaped, 15 mm$^{\varnothing}$ and 6.3 mm thick. The weight is M_s = 2.37g with a specific density of $\rho = 2.53$ g cm^{-3}. It is mechanical stable to 800 ^{o}C.

The ratio of B_4C in boral is: p = 0.35, the remaining part being Al.

Natural abundance of ^{10}B in B is $\nu = 0.196$. The formula weight of B_4C is

$$M_{(B_4C)} = 4 \cdot 10.80 + 12.01 = 55.25$$

The thermal neutron reaction

$${}^{10}_{5}B + {}^{1}_{0}n \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He$$

release the α-particles with energy E_α = 2.7 MeV.

The macroscopic cross section of the reaction is

NEUTRONDETECTOR FOR 1 VGR SILICON IRRADIATION FACILITY IN DR3

MATERIAL: STAINLESS STEEL

SCALE : 5 :1

T/C : 1,0 MM O.D. CROMEL/ALUMEL THERMOCOUPLE

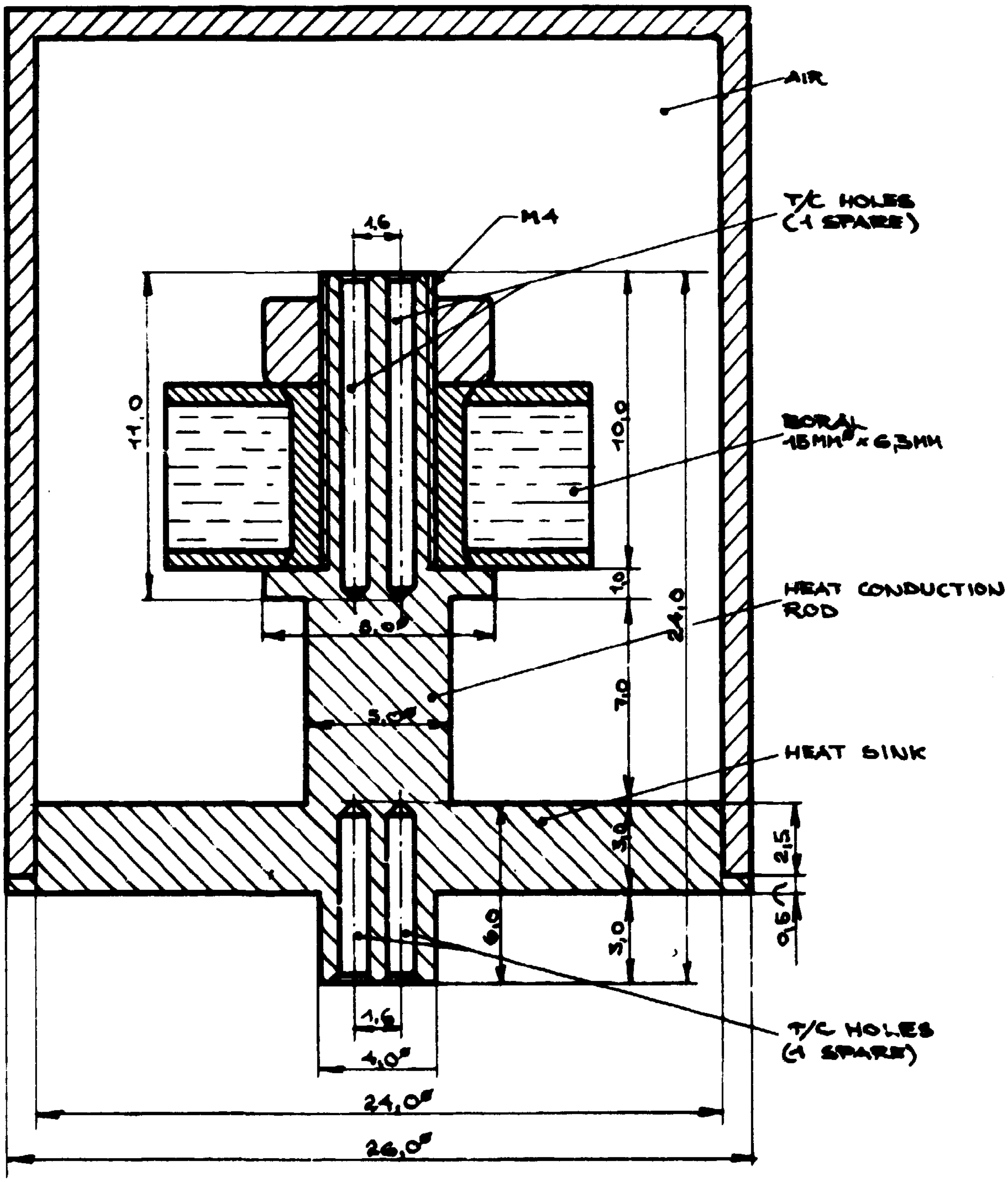

Fig. 1

$$\Sigma = \sigma \cdot \rho \cdot \frac{N_a}{M_{(B_4C)}} \cdot 4 \cdot p \cdot \nu =$$

$$3837 \cdot 10^{-24} \cdot 2.53 \cdot \frac{0.6023 \cdot 10^{24}}{55.25} \cdot 4 \cdot 0.35 \cdot 0.196 =$$

$$29.03\ \mathrm{cm}^{-1}$$

As the disc volume is

$$V_o = \frac{\pi}{4} \cdot (D_0^2 - d_0^2) \cdot t_0 = \frac{\pi}{4} (1.5^2 - 0.6^2) \cdot 0.63 =$$
$$0.94\ \mathrm{cm}^3,$$

the total cross section is

$$V_o\Sigma = 0.94 \cdot 29.03 = 27.15\ \mathrm{cm}^2.$$

The disc surface is

$$S = 2 \cdot d^2 \cdot \frac{\pi}{4} + 1.5 \cdot \pi \cdot 0.635 = 6.53\ \mathrm{cm}^2$$

As $\frac{S}{4} = \frac{6.53}{4} = 1.626\ \mathrm{cm}^2$ is less than to total cross section, $\frac{S}{4}$ must be applied as the total cross section. With this "black" absorber the flux depression factor is set to $\varkappa = 0.5$.

With a thermal neutron flux density

$$\phi = 4 \cdot 10^{12}\ \mathrm{n\ cm^{-2}s^{-1}}$$

the heating from the (n,α)-reaction in ^{10}B is

$$P_n = \frac{S}{4} \cdot \varkappa \cdot \phi \cdot \frac{E_\alpha}{6.24 \cdot 10^{12}}\ \mathrm{W}$$

$$= 1.626 \cdot 0.5 \cdot 4 \cdot 10^{12} \cdot \frac{2.7}{6.24 \cdot 10^{12}} = 1.40\ \mathrm{W} \qquad (1)$$

The nuclear heating of the sample structure ($M_{St} = 2.55g$) and the sample is

$$P_\gamma = (M_{St} + M_S)NH = (2.55 + 2.40) \cdot 0.020 = 0.10 \text{ W}$$

as the specific nuclear heating is

$$NH = 0.020 \text{ W/g in the 4-VGR-holes.}$$

The heat transport from the sample to the surroundings is accompanied by a temperature drop

$$\Delta T = \frac{P_n+P_\gamma}{L_R+L_G+L_{TC}} = \frac{1.40+0.10}{0.048+0.002+0.007} \approx \underline{\underline{26.3\ ^oC}} \qquad (2)$$

where:

L_R is the thermal conductivity of the rod:

$$L_R = \lambda_{SS} \cdot \frac{a_{SS}}{l_{SS}} = 0.17\ \frac{0.196}{0.7} = 0.048 \text{ W/}^oC$$

L_G is the air gap thermal conductivity:

$$L_G = \frac{2\pi\lambda_L}{\frac{1}{d_i} + \frac{1}{d_o}} = \frac{2\pi \cdot 3 \cdot 10^{-4}}{\frac{1}{1.4} - \frac{1}{2.8}} = 0.002 \text{ W/}^oC$$

L_{TC} is the thermocouple thermal conductivity:

$$L_{TC} = \lambda_{TC}\ \frac{a_{TC}}{l_{TC}} = 0.84 \cdot \frac{0.008}{1.0} = 0.007 \text{ W/}^oC$$

The air gap conductivity is considered roughly equivalent to the heat conduction between two concentric spheres with diameters

$$d_o = 2.8 \text{ cm} \quad \text{and} \quad d_i = 1.4 \text{ cm}$$

4. IN-CORE LIFE OF THE DOSEMETER

The time dependance of the calorimeter ΔT-signal can be estimated by assuming that the boral disc is burned up layer by layer from all directions.

In the burn-up depth x cm the total cross section will be:

$$\frac{S_x}{4} = \frac{1}{4}(2(d-2x)^2 \cdot \frac{\pi}{4} + (d-2x)(t-2x) \cdot \pi)$$

$$= 1.5\pi x^2 - 1.815\pi x + 1.626 \tag{3}$$

and the number of ^{10}B atoms in the layer dx at the burn-out depth x is:

$dN_x = S_x \cdot d_x \cdot \frac{\Sigma}{\sigma}$ where $\frac{\Sigma}{\sigma}$ is the number of ^{10}B nuclei per cm^3 of the sample.

As the reaction rate at that moment is

$$\frac{dN_x}{dt} = \varkappa \cdot \phi \cdot \frac{S_x}{4} \tag{4}$$

we find

$$t = \int_o^t dt = \int_o^x \frac{4}{\varkappa \phi S_x} dN_x = \frac{4\Sigma}{\varkappa \phi \sigma} \int_o^x dx = \frac{4\Sigma}{\varkappa \phi \sigma} x$$

$$= \frac{4 \cdot 29.03}{0.5 \cdot 4 \cdot 10^{12} \cdot 3837 \cdot 10^{-24} \cdot 3.1557 \cdot 10^7} = 479.5 \cdot x \text{ years} \tag{5}$$

with given neutron flux density $\phi = 4 \cdot 10^{12}$ n $cm^{-2}s^{-1}$. Substituting eq. (5) in eq. (3) we obtain:

$$\frac{S_x}{4} = 2.050 \cdot 10^{-5} t^2 - 1.189 \cdot 10^{-2} t + 1.626 \tag{6}$$

Assuming that the nuclear heating is proportional to the thermal flux density, we obtain from eq. (2) and eq. (1):

$$\Delta T = \frac{\frac{S_x}{4}\,\kappa\phi \cdot \frac{\varepsilon_\alpha}{6.24 \cdot 10^{12}}\left(1+\frac{P_\gamma}{P_n}\right)}{L_R + L_G + L_{TC}}$$

$$= \frac{0.5 \cdot 4 \cdot 10^{12}\,\frac{2.7}{6.24 \cdot 10^{12}}\left(1+\frac{0.10}{1.40}\right)}{0.048 + 0.002 + 0.007} \cdot \frac{S_x}{4} = 16.27 \cdot \frac{S_x}{4} \quad (7)$$

and consequently, by combining eqs. (6) and (7):

$$\Delta T = 3.335 \cdot 10^{-4} t^2 - 0.193t + 26.47 \quad (8)$$

This function is shown in fig. 2. The disc is burned out, when

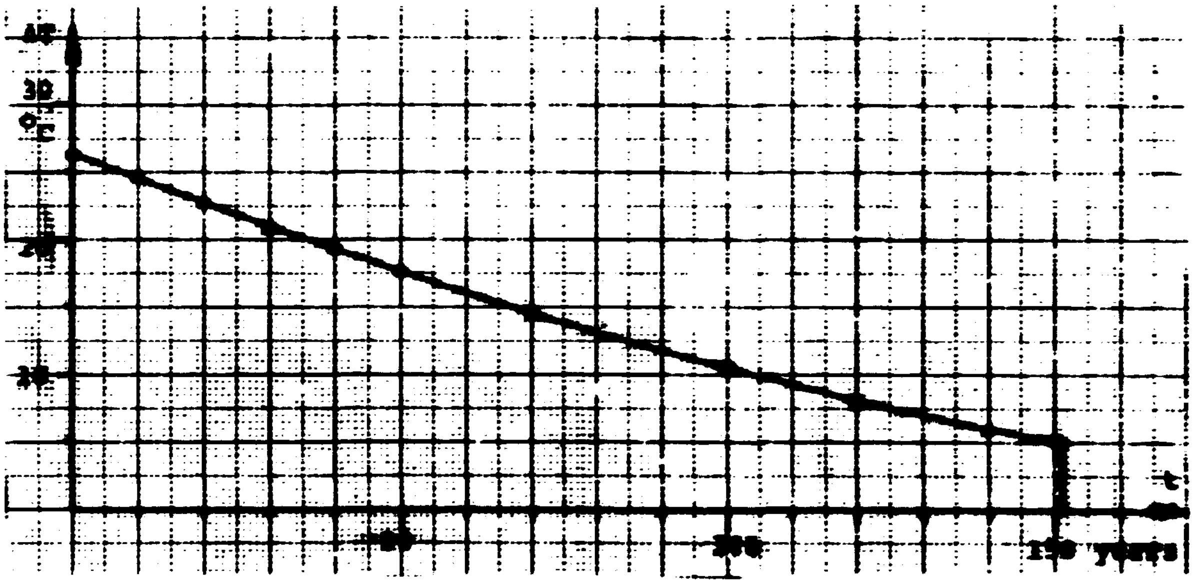

Fig. 2. The calorimeter-response's time-dependence at constant thermal neutron flux density.

x equals the half thickness of the disc, e.g. after

$$t = 479.5 \cdot \frac{0.63}{2} = 151 \text{ years.}$$

The initial decrease of the calorimeter response per year is

$$\left(\frac{d(\Delta T)}{dx}\right)_{x \to 0} = -0.193\ {}^{o}C\ yr^{-1}$$

or

$$\frac{0.193}{26.47} \cdot 100 = 0.72\%\ \text{per year.}$$

5. INSTRUMENTATION

The calorimeter output signal is in the mV-range. In order to perform a time integration of this signal and to trig a warning bell circuit when a certain preset dose is gained, an instrumentation as shown on fig. 3 is used.

The input unit is an operation amplifier with 10^3 amplification of the mV signal. The output from this unit is converted to a frequency signal having passed a calibration potentiometer. The optocoupler provides a galvanic separation of the counter and logic circuits. The frequency is reduced by a factor of 10^3 and counted in a 6 decade counterchain, which count down a preset value on the display. When the display shows 1000 counts a pre-warning is given by the comparator, which turns the flip-flop circuit over. A final warning is given when the display read zero. This enable the operator to withdraw the irradiated crystal just in time. The system can be reset manually on the rack or remote through an amplifier/optocoupler chain.

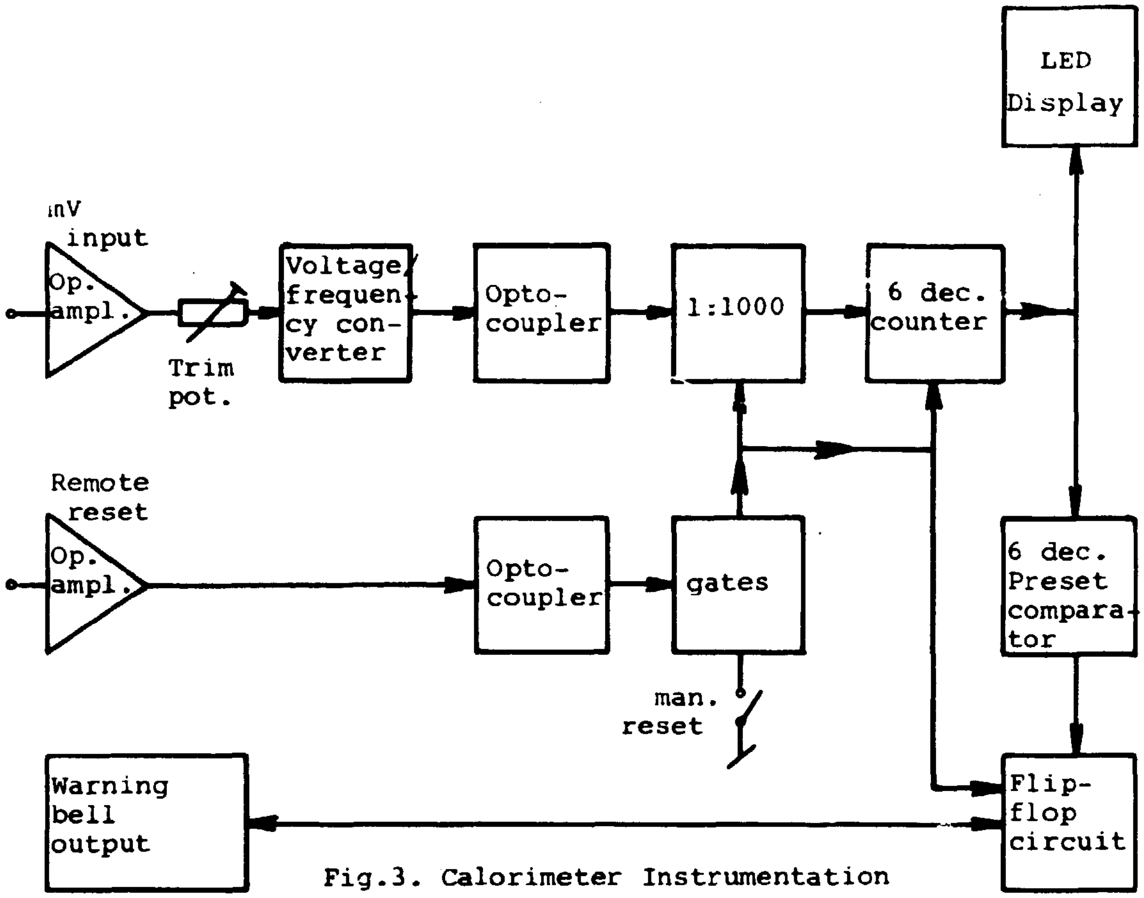

Fig.3. Calorimeter Instrumentation Block diagram.

Input range is 0.5 - 10 mV
1 mV input in 50 hours displays 180.000 counts
Stability: Max. 0.2% per ^{o}C
Drift: Typical 1.5% per year.

6. PERFORMANCE

The calorimeter was checked in a test rig with an aluminium cylinder for simulation of the Si-crystal. The rig was equipped with three 6 mm$^{\varnothing}$ i.d. flux scan tubes to facilitate Cobolt flux scanning in the centre and on the sides of the Al-cylinder, 180^{o} apart.

The calorimeter output was around 1.09 mV (ΔT 26.6 ^{o}C) with a linear decrease of 2% during the test run.

The corresponding thermal neutron flux density measurements at the beginning, the mid and the end of the test run showed a decrease of about 1%. The mean thermal neutron flux density at the spot where the calorimeter was placed was $3.8 \cdot 10^{12}$ x) acc. to the Co flux scannings. The corresponding estimated calorimeter response can be derived from eq. (1) and eq. (2), section 3:

$$\Delta T = 26.47 \cdot \frac{3.8}{4.0} = 25.1\ ^{o}C$$

One silicon irradiation rig was put in commercial operation in 1976. In 1977 another 4 rigs were installed, all in the 4-VGR-holes. The results from the operation of these 5 rigs until November (1980) are treated in a report [1] which was presented at the international conference in Copenhagen, August 1980, on Neutron Transmitation Doped Silicon. According to [1] the standard deviation of an estimated calibration value is 1.1 - 1.2% and the actual measurement of integrated dose is carried out with a precision of 1.2 - 1.4%.

7. REFERENCES

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K.H. BECKURTS and K. WIRTZ (1964). Neutron Physics. Springer-Verlag Berlin.

x) Unperturbed flux

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Title and author(s)

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by

Karsten Haack

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